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Diesel Engine Evaluation of a Nonionic Sunflower Oil-Aqueous Ethanol Microemulsion[1]

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ABSTRACT

A nonionic sunflower oil-aqueous ethanol microemulsion was formulated, characterized and evaluated as a fuel in a direct injection, turbocharged, intercooled, 4-cylinder Allis-Chalmers diesel engine during a 200 hr EMA cycle laboratory screening endurance test. Differences in engine operation between a baseline Phillips 2D reference fuel and the experimental fuel were observed. The major problem experienced while operating with the microemulsion was an incomplete combustion process at low-load engine operation. Significant lubricating oil dilution was observed initially, followed by an abnormal increase in the viscosity of the lubricative oil. Heavier carbon residue on the piston lands, in the piston ring grooves and in the intake ports was noted. In addition, premature injection-nozzle deterioration (sticking of the needle) was experienced. At present, the sunflower oil-aqueous ethanol microemulsion studied cannot be recommended for long-term use in a direct-injection diesel engine, but further modifications in formulation may produce acceptable sunflower oil microemulsions as alternative diesel fuels.

INTRODUCTION

Agriculture and industry use diesel-powered engines for many purposes, but the supply of diesel fuel is limited. Neat vegetable oils are too viscous for prolonged use in direct-injected diesel engines. Viscosity can be reduced by (a) heating the vegetable oil to sufficient temperatures to lower the viscosity to near specification range, (b) converting the vegetable oil to the simple esters of methyl, ethyl or butyl alcohols or (c) diluting the vegetable oil with other, less viscous, liquid fuels, forming blends that have been termed hybrid fuels or (d) by microemulsification (1). Microemulsions of aqueous ethanol in triglyceride oils remain as clear, thermodynamically stable liquid fuels with viscosities near the ASTM specified range for No. 2 diesel fuel. They are generally accepted as micellar systems and may be classified as detergent or detergentless. Goering et al. (2) evaluated the short-term performance of both ionic and nonionic microemulsions of aqueous ethanol in soybean oil. These fuels performed nearly as well as No. 2 diesel despite having lower cetane numbers and less energy content. However, the effects of the hybrid fuels on engine durability were not determined. This manuscript will present data on an EMA 200 hr engine screening durability test of a nonionic sunflower oil-aqueous ethanol microemulsion.

EXPERIMENTAL PROCEDURES

Materials

The sunflower oil used was refined with alkali and winterized and was obtained from Honeymead Products, Mankato, MN. Gas liquid chromatography (GLC) analysis showed a composition of 69.3% linoleic, 18.7% oleic, 6.0% palmitic, 4.2% stearic, 1.0% behenic, 0.4% arachidic and 0.1% eicosenoic acids. Wax content of the sunflower oil was 90 ppm (3). Commercial grade 95% ethanol was obtained from Midstates Energy Resource, Lanark, IL, and, at 25 C, had a specific gravity of 0.8169. 1-Butanol was acquired from Worum Chemical, St. Paul, MN, and had a boiling range of 116-118 C. Phillips 2D reference fuel was obtained from Phillips Chemical Co., Barger, TX. The distillation range was from 190 C to 325 C, with an aromatic content of ca. 30%.

Methods

Viscosities were determined using Cannon-Fenske viscometers in a Scientific Development kinematic bath at 37.8 C (100 F). Tests were conducted by ASTM method D 445-74 (4). The composition of sunflower oil was determined by GLC analyses. Standard American Oil Chemists' Society (AOCS) methods used include: preparation of methyl esters for GLC (5), GLC analysis (6), acid values (7) and peroxide values (8). Cetane number of the microemulsion was determined by a modification of ASTM D 613 procedure (9).

Microemulsion Preparation

The microemulsion was prepared in a 500 gal tank by charging with 240 gal alkali-refined and winterized sunflower oil, 60 gal 190-proof ethanol and 150 gal 1-butanol. This microemulsion composition is 53.3% (vol) sunflower oil, 13.3% (vol) 190-proof ethanol and 33.4% (vol) 1-butanol, and it remains a homogeneous single-phase system down to 15 C. The fuel properties of this microemulsion are listed in Table I along with properties of the control diesel fuel.

TABLE I

Test Fuel Properties

Property	D-2 Control diesel fuel	Nonionic microemulsion
Pour point, C	-29	[a]
Critical solution temperature, C	-20	15
API gravity @ 15.6 C	35.5	31.3
Heat of combustion, KJ/kg		
Gross	45,422	36,393
Net	42,668	33,592
Heat of combustion, KJ/L		
Gross	38,399	31,559
Net	36,071	29,130
Viscosity @ 40 C, cs.	2.37	6.31
Viscosity @ 100 C, cs.	--	2.16
Cetane number	50.1	25
Ash, %	<0.01	<0.01
Carbon, %	86.92	70.78
Hydrogen, %	12.46	13.20
Sulfur, %	0.23	0.01
Flash point, PMCC[b], C	--	27
Peroxide value, meq/1,000 g	--	15.99
Total acid no., mg KOH/g	--	0.02
Free fatty acids, %	--	0.01
Iodine value	--	72.6

[a] The sample exhibits a cloud point at 26 C. At 2 C the sample separated into two phases. The lower (white) layer solidified at -29 C; the upper (pink to yellow) layer was still liquid at -65.0 C.

[b] Penske-Martin closed cup.

[1] Presented at the AOCS meeting, Chicago, IL, May 1983.

Test Procedure

A 4-cylinder Allis-Chalmers model 433I turbocharged and intercooled 4-stroke cycle diesel engine was used for fuel evaluation. The engine and fuel-injection system specifications are listed in Table II. The engine was operated on a screening test cycle recommended by the Alternate Fuels Committee of the Engine Manufacturer's Association (EMA) (10). The cycle was repeated 5 times. After 15 hr on the cycle, the engine was shut down for 9 hr. This procedure was repeated until 200 hr of operation on the test cycle had been completed. Average cycle power was maintained at ca. 70%. Engine load was applied with a Dynamic Absorbing Dynamometer Model 1014 D.G. A Hytress III Simulator System was used to simulate the programmed engine cycle, which was recorded on magnetic tape in frequency modulated (FM) form. During a test, a frequency signal from the magnetic tape was filtered and conditioned in the signal-conditioning chassis. A feedback signal was derived from the engine speed, engine torque and throttle position transducers. The Frequency Comparator Circuit compared the command from the tape with the feedback signal and caused an actuator to change the control parameter in the appropriate direction to eliminate error. Fuel injection line pressure was measured at the nozzle with a Kistler Model No. 607F122 piezoelectric pressure transducer and the pressure output signals were conditioned with a charge amplifier. Outputs from the pressure transducer and magnetic sensor were displayed on a Nicolet Instrument Corporation Explorer III digital oscilloscope and stored in a Tektronix 4052 Graphic Computer System. Fuel consumption was measured on a weight basis with a Cox Instrument Fuel Consumption Weight System, Type 402. A Robert Bosch (RB) Model EFAW 68A smokemeter was used to analyze exhaust smoke.

RESULTS AND DISCUSSION

Figure 1 is a graph showing kinematic viscosity vs percentage of 1-butanol in sunflower oil/95% ethanol/1-butanol microemulsions. Fuel viscosity has a pronounced effect on lubrication of the injection system, and, in addition, the spray pattern produced by the injection nozzle is a function of fuel viscosity. With increasing amounts of 1-butanol, lower viscosities and better spray patterns are obtained, but the cetane number is lowered. Cetane number is a measure of ignition quality of the fuel, and its significance to vegetable oils has not been established (11).

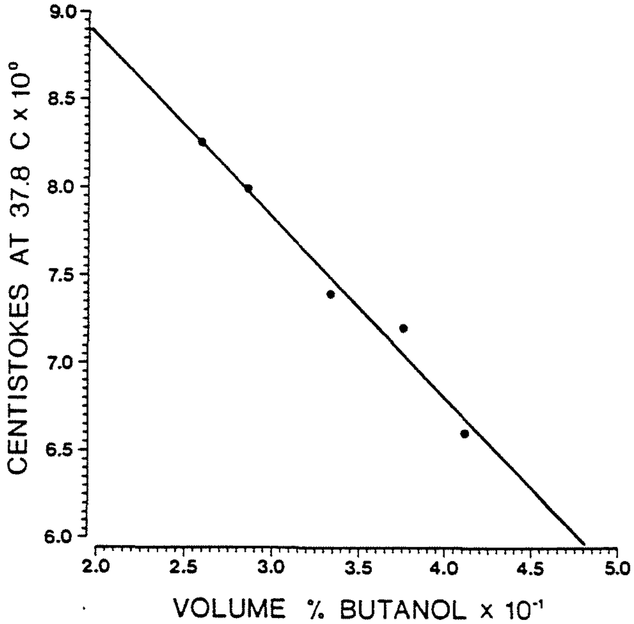

FIG. 1. Kinematic viscosity vs concentration of 1-butanol in a sunflower oil 95% ethanol system (volume ratio of sunflower oil to ethanol is 4 to 1).

Figure 2 shows percentage distilled vs. temperature for the microemulsion and No. 2 diesel fuel. Above 250 C, cracking was observed for the microemulsion. Ca. 97% of the microemulsion was distillable, accompanied by pyrolysis at vapor temperatures up to 323 C. Cracking was observed at ca. 250 C during this distillation, but distillation

TABLE II

Engine and Fuel-Injection System Specifications

Description	Specification
Engine model	433I, turbocharged and intercooled
Type	Four-stroke cycle
Combustion system	Direct injection, high swirl, torroidal combustion chamber
Bore/stroke	98.43 mm/107.95 mm
Compression ratio	14.5:1
Maximum output	74.6 kW @ 2,400 rpm
Maximum torque	329.5 Nm @ 1,800 rpm
Static injection timing	18 degrees before top dead center
Hydraulic speed advance	14 degrees advance between 1,400 and 1,600 rpm
Injection nozzle	Robert Bosch, 21-mm nozzle and holder assembly
Nozzle opening pressure	27.0 MPa ± 1%
Nozzle assembly	Four orifices: 0.32 mm diameter Spray cone angle: 160° Sac length: 1.1 mm Sac diameter: 1.0 mm
High-pressure fuel lines	1.83 mm ID x 815.60 mm

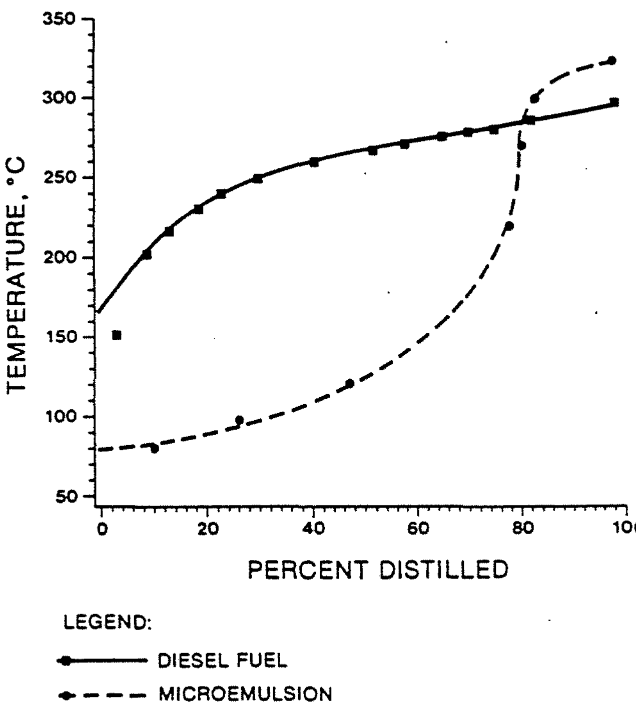

FIG. 2. Fuel distillation curves.

was continued as long as distillate was collected. On completion, a charred residue remained in the flask, the amount of which was determined by weighing before and after cleaning the flask. This residue amounted to ca. 3% of the total fractions collected.

Although the EMA recommends 200 hr of operation on their screening test cycle, the engine accumulated more total hours of operation because of the time needed to record performance data and pressure readings of the fuel injection line throughout the test. The engine operated for 321 hr while using diesel fuel and for 257 hr while using the microemulsion. For both tests, the engine completed 200 hr of the EMA cycle without requiring a fuel filter change. During the entire test, the pressure before the fuel injection pump at rated speed was maintained between 20-28 kPa, which fulfills the manufacturer's specifications. During the test on the microemulsion, ether assists were used to start the engine between the 15 hr cycles.

Engine Performance

Figure 3 shows fuel flow and energy input for the microemulsion and reference fuel at various engine speeds on the power curve. The higher viscosity of the microemulsion contributed to an increased mass fuel flow by reducing internal pump leakage. However, the higher mass fuel flow for the microemulsion was not sufficient to compensate for a heating value 19% lower than for diesel fuel. The difference in energy delivery over the tested engine speed range was uniform.

The initial engine performance and operating conditions for diesel fuel and the microemulsion are reported in Figure 4. Engine power output for the microemulsion was 8% lower than the power observed with diesel fuel. When diesel fuel was replaced by the microemulsion, the specific energy consumption improved by 4%. Also, the RB smoke number dropped from 1.5 to 0.2 at 2,300 rpm and from 2.5 to 0.5 at 1,800 rpm. In addition to the lower combustion efficiency, a higher exhaust temperature and higher intake manifold pressure for diesel fuel were caused by greater energy delivery per unit of time. Figure 5 shows the engine performance and operating conditions recorded at

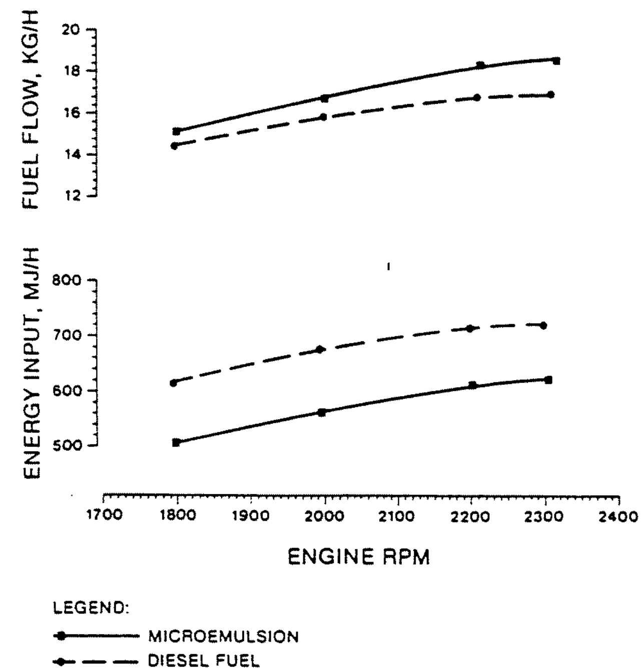

FIG. 3. Fuel flow (kg/hr) and energy input (MJ/hr × 10^2) as a function of engine rpm for tested fuels.

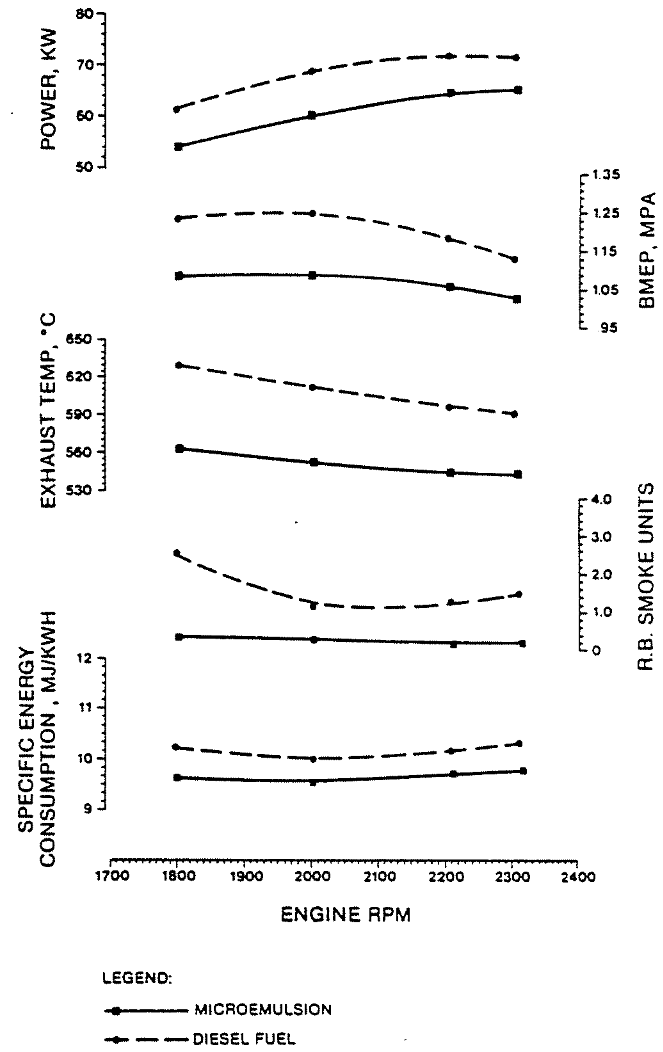

FIG. 4. Initial comparative engine performance between diesel fuel and the nonionic sunflower oil-aqueous ethanol microemulsion.

the beginning and end of the test on the microemulsion. The engine performance throughout the entire test was adequate. No significant deterioration was observed.

Nozzles and Injection Pump

During 257 hr of engine operation on the microemulsion, one set of injection nozzles was used. Table III summarizes nozzle performance after 0, 30, 135 and 200 hr of the EMA cycle. The injector needles stuck sporadically for various nozzles. After 30 hr of the EMA cycle, 2 nozzles (#1 and #4) were leaking and had improper chatter. After 135 hr of the EMA cycle, nozzles #2 and #4 had improper chatter, and injection nozzle #2 was reassembled. At the completion of the test, only nozzle #4 showed weak chatter. The final nozzle opening pressure drop was 6.5% for 2 nozzles and 5% for the remaining 2 nozzles. Figure 6 shows that nozzles tips displayed carbonaceous residue that did not appear to block any orifices. Carbon and lacquer buildup on the nozzle needle over a period of time caused the needle movement in the housing to become difficult. Ziejewski and Kaufman (12) have noted that sporadic nozzle-needle sticking did not directly affect the specific fuel consumption, but could cause the formation of carbon deposits on the nozzle tip, nozzle needle and nozzle seat, which may cause poor seating with consequent dribble. Greeves et al. (13) observed that fuel, which remains or is introduced into the nozzle tip after the end of the main

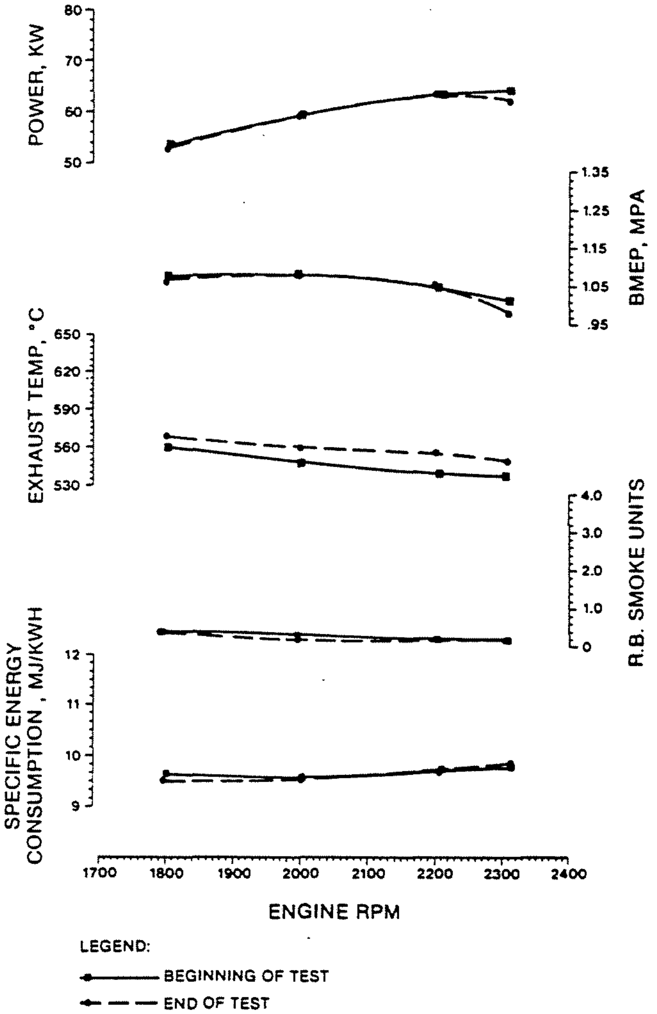

FIG. 5. Engine performance at beginning and end of EMA test cycle using nonionic sunflower oil-aqueous ethanol microemulsion.

FIG. 6. Carbon buildup on the injection nozzle tip after the test on microemulsion.

injection, leaves the tip because of fuel evaporation and high gas flow. Borman and DeLuca (14) postulate that fuel trapped between injections undergoes thermal decomposition, which is influenced by the chemical composition of the fuel and by the presence of catalytic materials such as carbon. The fuel injection pump performed properly throughout the test on the microemulsion. However, excessive deposits on the internal parts of the pump and an increase in the flexibility of a flexible ring in the weight cage were recognized.

TABLE III

Injection Nozzle Test Stand Analysis

Nozzle No.	Opening pressure MPa	Pressure drop time s	Chatter	Leak	Orifice diameters mm
Condition at installation date:					
1	26.9	12	vg	no	0.32, 0.32, 0.32, 0.32
2	26.9	15	vg	no	0.32, 0.32, 0.32, 0.32
3	26.9	11	vg	no	0.32, 0.32, 0.32, 0.32
4	27.2	14	vg	no	0.32, 0.32, 0.32, 0.32
After 30 hr of EMA cycle, 48 hr total					
1	26.9	17	Fair	yes	----
2	26.9	27	vg	no	----
3	25.9	24	vg	no	----
4	27.6	20	Poor	yes	----
After 135 hr of EMA cycle, 181 hr total					
1	26.2	11	vg	no	----
2	26.2	21	no	no	----
3	25.5	22	vg	no	----
4	25.9	14	Poor	no	----
After 200 hr of EMA cycle, 257 hr total					
1	25.5	15	Good	no	0.32, 0.31, 0.318, 0.318
2	25.2	25	Good	no	0.318, 0.318, 0.31, 0.318
3	25.5	22	Good	no	0.32, 0.318, 0.32, 0.32
4	25.5	22	Fair	no	0.32, 0.318, 0.32, 0.32

Lubricating Oil

The lubricating oil consumption for the test on diesel fuel was adequate at 16.05 g/hr. However, throughout the run on the microemulsion, lubricating oil consumption varied (Fig. 7). Several times, the level of the lubricating oil increased, indicating significant fuel dilution of the oil. Oil samples, taken every 15 hr, were used to determine any changes in kinematic viscosity and dispersive characteristics. Figure 8 shows kinematic viscosity plotted vs time for lubricating oil during the microemulsion test. After 60 hr of the EMA cycle (80 hr since the last lubricating oil was changed), a 50% change of kinematic viscosity was noted. After 120 hr of the EMA cycle (78 hr since the lubricating oil was changed), a sudden increase in lubricating oil viscosity from 108 cP to 2280 cP was observed. At the same time, higher blow-by and increased lubricating oil consumption was observed. Except for the samples of the lubricating oil for the microemulsion test at 60 hr and 120 hr of the EMA cycle, analysis of the "Blotter spot" samples did not indicate any abnormal changes in the lubricant dispersive characteristics for both tests.

Engine Teardown and Final Inspection

After each durability test, the carbon, sludge and varnish deposits were rated using the Coordinating Research Council (CRC) test procedure (15). The wear of the engine parts was determined by direct measurement.

Cylinder head, intake and exhaust valves. For both tested fuels the combustion area of the cylinder head showed light, uniform, flat carbon buildup. The manifold and combustion side of the exhaust port, as well as the manifold side of the intake port, appeared clean. The combustion side of the intake port of the engine tested on the diesel fuel showed soft, oily, uniform carbon buildup, whereas the engine run on the microemulsion exhibited black, rubber-like, nonuniform, shiny residue. A greater amount of hard

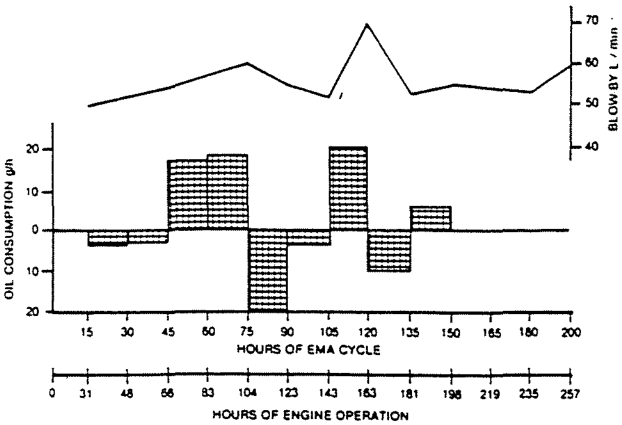

FIG. 7. Oil consumption and blow-by of microemulsion fuel.

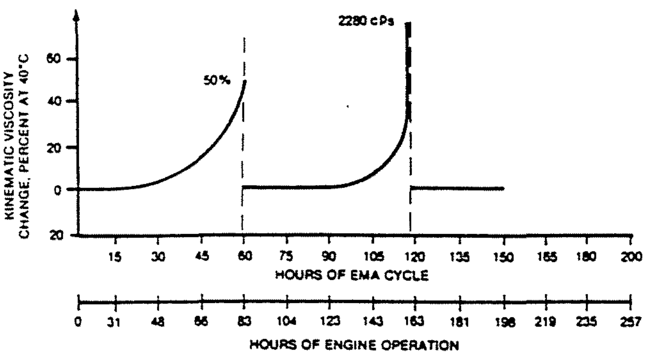

FIG. 8. Kinematic viscosity change for microemulsion fuel.

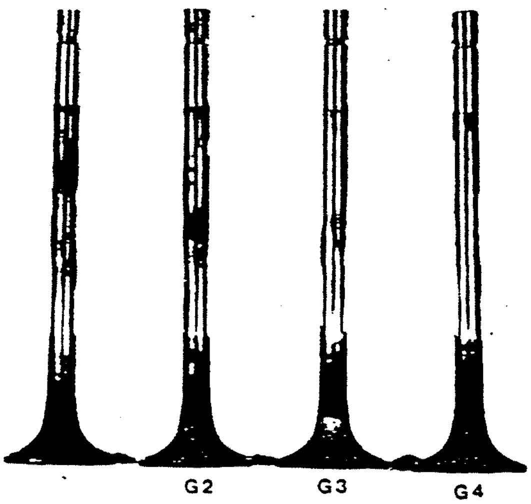

FIG. 9. Carbon buildup on the exhaust valves after the test on microemulsion.

black buildup was visible underneath the seat for the microemulsion test. The average CRC rating for the intake passages was 1.40 for the microemulsion test and 1.13 for the diesel fuel test, where the higher number corresponds to a poorer rating.

No difference in the intake and exhaust valve seat conditions was detected for the tested fuels. The seating was satisfactory, but a light carbon buildup was distributed on the circumference of the seats. For both tests, all valve seats as well as all valve faces showed light peening caused by hard particles released from combustion chamber deposits. Light carbon residue on the intake valve faces and amber lacquer on the valve stems were noted. Figure 9 shows carbon buildup on exhaust valves for the microemulsion run. Difficulty in movement of exhaust valves because of carbon buildup on the valve stems caused pistons #1, #2 and #4 to hit the exhaust valves (Fig. 9). Subsequently, exhaust valve stem deformation occurred.

Cylinder sleeves. After the 200-hr test on the microemulsion, heavy carbon residue was observed on the cylinder sleeves above the top ring travel area. The average CRC rating for the carbon deposits was 1.10 for the diesel fuel test and 1.77 for the microemulsion test. For all sleeves after the microemulsion run, random scratching and light polish tracks were recognized above and below the lowest level of ring travel. High magnification revealed that most of the scratches were superficial. However, some of the scratches on the sleeves were noticeably deeper than the hone marks. As indicated by the scratches extending below the lowest level of ring travel and the smearing of metal on the sides of the piston, the scratching was caused partially by the piston rather than by the rings. Some sleeve scratches were also generated by dirt particles in the lubricating oil. The location of the first, second, third and oil ring turnaround was visible for all 4 sleeves.

Piston and rings. The pistons did not exhibit any sign of cracking, but all pistons showed significantly greater carbon and lacquer buildup in the ring grooves and on the piston lands, undercrowns and skirts. The second ring for pistons #3 and #4 and the third ring for piston #2 were partially stuck at 180° of circumference on the antithrust side. Figure 10 shows carbon buildup on the piston after completion of tests with the microemulsion. On the fourth land, black, dark brown and amber lacquer residue was observed for the microemulsion test, but the fourth land appeared clean for the diesel fuel test. All deposits from the test on the microemulsion were hard and shiny and did not flake off, unlike the dry carbon buildup formed during the run on diesel fuel. Table IV lists CRC rating data for piston ring groove after running 257 hr on the microemulsion fuel. The deposits for the microemulsion were significantly larger than those measured for the diesel fuel. The CRC ratings reported in Table V indicated significantly heavier carbonaceous piston land deposits for the microemulsion test than for the diesel fuel run. Figure 11 shows that the undercrown of piston #1 was covered by a dark brown lacquer residue, contrary to the clean piston undercrown after the diesel fuel run. This phenomenon was partially caused by possible lubricating oil starvation and subsequent piston

FIG. 10. Carbon buildup on the piston after the durability test with the microemulsion.

TABLE IV

Piston Ring Groove CRC Rating After Microemulsion Test

Location		Sticking	Bottom groove lacquer	Groove filling carbon		Groove side			
						Lacquer		Carbon	
				Vol. %	CRC	Top	Bottom	Top	Bottom
Top	Mean	Free	0	90	2.4	0	0	0.6	0.2
	S.D.		0	10	0.2	0	0	0.2	0.2
2	Mean	Two partially stuck	0	62.5	1.8	0	0	0.8	0.5
	S.D.		0	31.8	0.6	0	0	0.1	0.4
3	Mean	One partially stuck	0	25	1.05	0	0	0.6	0
	S.D.		0	0	0	0	0	0.[illegible]	0
4	Mean	Free	6.1	3.1	0.3	4.13	0.38	0	0
	S.D.		1.5	3.75	0.5	2.36	0.75	0	0

TABLE V

Piston Land Deposit CRC Ratings

Surface	D-2 Diesel control fuel				Microemulsion			
	Lacquer		Carbon		Lacquer		Carbon	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Piston crown	0	0	1.03	0.04	0	0	1.05	0
Top land	0	0	1.47	0.25	0	0	1.92	0.14
2nd Land	0.88	0.25	1.27	0.04	0	0	1.51	0.16
3rd Land	1.69	0.99	0	0	0	0	1.05	0
4th Land	0	0	0	0	6.06	1.51	0	0
Piston skirt	0	0	0	0	0.78	0.52	0	0
Undercrown	0.85	0.19	0	0	4.88	0.18	0	0
Pin bore - Front	0	0	0	0	0	0	0	0
Pin bore - Rear	0	0	0	0	0	0	0	0
Piston pin	0	0	0	0	0	0	0	0
Oil hole	0	0	0	0	2.5	0	0	0

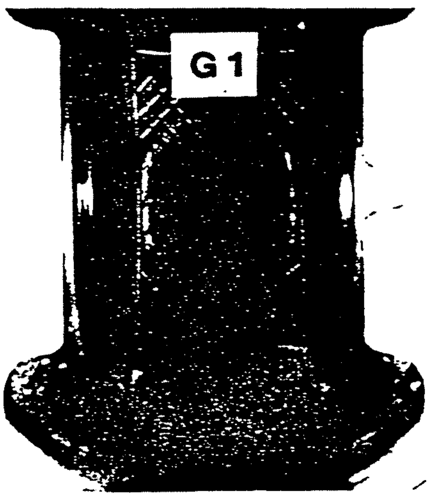

FIG. 11. Lacquer residue buildup on the undercrown of the piston after the microemulsion test.

overheating at 60 hr and 120 hr of the EMA cycle, when a significant increase in the viscostiy of lubricating oil occurred.

The average CRC rating for piston land deposits is presented in Table V, and the average CRC rating for piston ring carbon deposits is reported in Table VI. Significant differences are noted between the 2 fuels. Inspection of the piston combustion chamber after the microemulsion test did not reveal any evidence of a denser fuel spray core. The fuel vapor and fuel flame reflection areas from the combustion chamber wall corresponded to the geometry of the multi-hole nozzle and were light and uniform. The reflection areas were surrounded by light, soft carbon residue. Fifteen percent of the piston crown surface had an accumulation of light, uniform gray ash deposits. Figure 12 shows carbon and ash buildup on the piston #1 combustion chamber wall after 257 hr of operation with the microemulsion fuel. The carbon residue, vapor and areas where flame impinged were smaller and more uniform for the reference fuel than for the microemulsion fuel.

TABLE VI

Piston Ring Deposit CRC Ratings

Location		D-2 Diesel control fuel				Microemulsion			
		Top	Bottom	Back	Front	Top	Bottom	Back	Front
Top	Mean	0.17	0	1.05	0	0.44	0.25	1.03	0.20
	S.D.	0	0	0	0	0.24	0.11	0.05	0.13
2	Mean	0.51	0.53	1.05	0.30	0.51	0.41	1.05	0.41
	S.D.	0	0.61	0	0.08	0	0.11	0	0
3	Mean	-	-	-	-	-	-	-	-
	S.D.	-	-	-	-	-	-	-	-
4[a]	Mean	0	0	0	0	3.31	2.06	4.88	7.5
	S.D.	0	0	0	0	1.43	0.38	2.25	1.06

[a]For ring #4 - lacquer residue was rated.

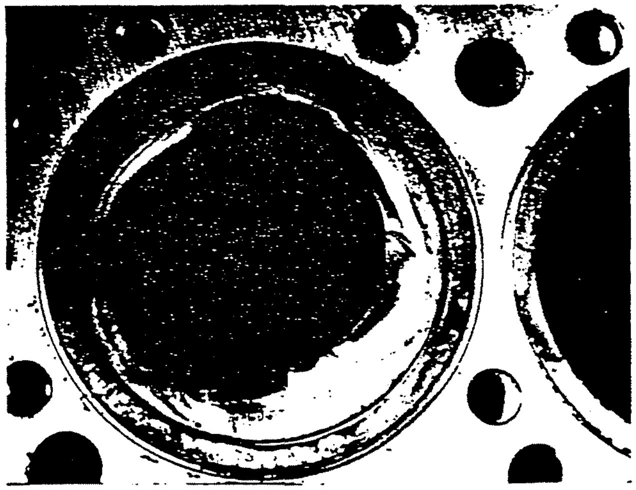

FIG. 12. Carbon and ash buildup on the piston #1 combustion chamber wall after the microemulsion test.

Bearings, turbocharger and engine measurements. Rod and main bearings were in good condition. No deposits were visible. All bearings showed a normal wear pattern. Turbochargers were in satisfactory condition, but the carbonaceous buildup on the turbocharger tested with the microemulsion fuel had a sticky, oily appearance. The turbine wheels were covered with normal light carbon residue. Compared with initial measurements, the final measurements for the engine did not indicate significant wear.

GENERAL OBSERVATIONS

Based on the results of this investigation, the nonionic sunflower oil-aqueous ethanol microemulsion tested could not be recommended for long-term use in a direct-injected diesel engine. General observations showed the following results. An increase in fuel mass flow caused by the higher density and viscosity of the microemulsion. A lower energy input because of the 19% lower heating value, with consequent lower power output, exhaust temperature and intake manifold pressure. A decrease in specific energy consumption and smoke. Difficulty in starting the engine at room temperature (starting aids were required). Sporadic sticking of the injector needle for various nozzles. The final nozzle opening pressure drop was 6.5% for 2 nozzles and 5% for the remaining 2 nozzles. Inspection showed only a slight reduction in orifice diameters for all nozzles. Excessive deposits on the internal parts of the fuel injection pump and an increase in the flexibility of a flexible ring in the weight cage. Lubricating oil consumption was not consistent. Significant fuel dilution of the lubricating oil was observed until after ca. 80 hr of engine operation, then a sudden increase in viscosity was measured. An incomplete combustion process (slobber from the turbocharger and blue smoke) occurred during engine starting and low load conditions. Shiny residue was deposited in the intake port and on the intake valve tulipis, and a light amber lacquer was deposited on the intake valve stems. Heavier carbon residue was visible on the cylinder liners above the ring travel area on the front, thrust and rear sides. Pistons #1, #2 and #4 hit the exhaust valves because of difficulty in exhaust valve movement caused by carbon buildup on the valve stems and in the valve guides. The undercrown of all pistons was covered by dark-brown lacquer deposits and the second ring was partially stuck (cold stuck, 180° of circumference, antithrust side) for pistons #3 and #4. The third ring was partially stuck (cold stuck, 180° of circumference, antithrust slide) for piston #2. Light carbon buildup covered 100% of the third piston lands and a black, dark-brown and amber lacquer residue appeared on the fourth piston lands. The oil ring surface was covered 100% by black and amber lacquer, and all piston compression ring grooves showed heavy carbon buildup. Black and amber lacquer buildup was observed on the piston skirts. Further investigations and tests are necessary before sunflower oil/aqueous ethanol/1-butanol microemulsions can be considered as alternate fuels for diesel engines.

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